



How the Sun Knocks Out My Cell Phone from 150 Million Kilometers Away

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Radiation Effects And Analysis Group

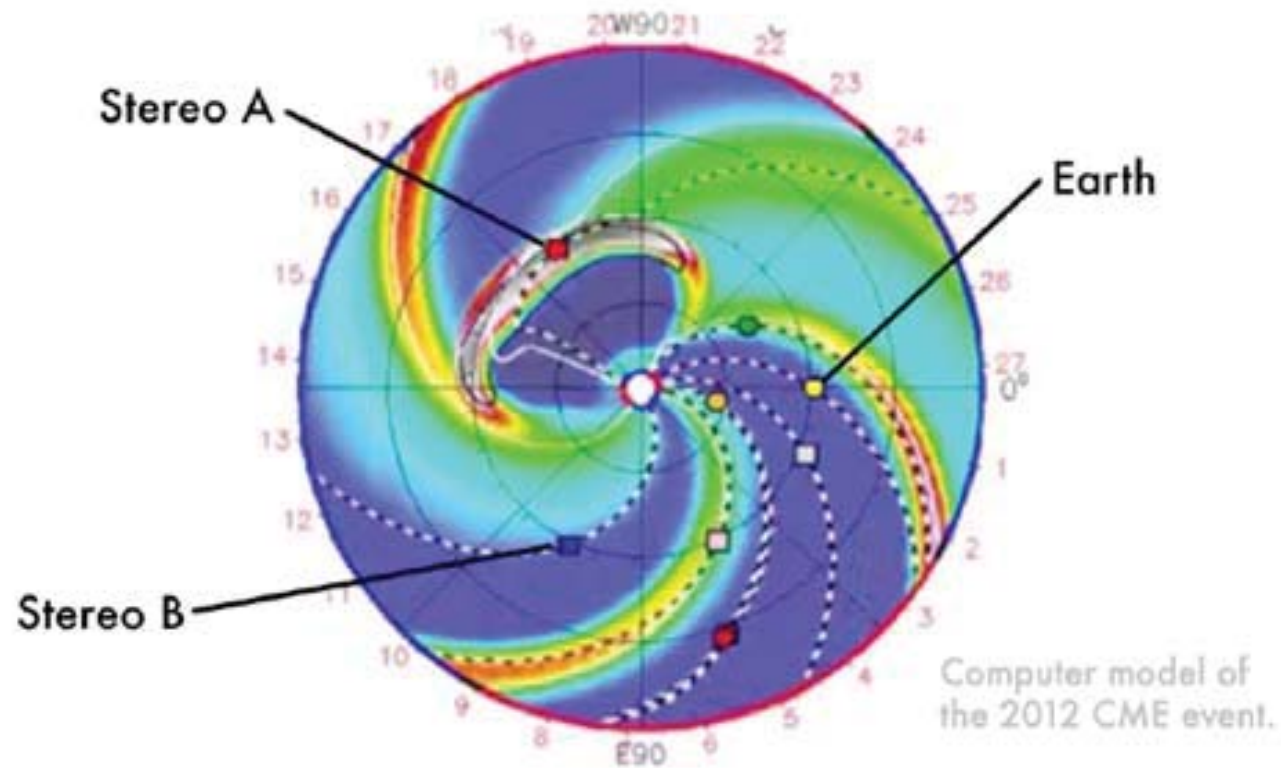
NASA Goddard Space Flight Center



Abbreviations

- ACE—Advanced Composition Explorer
- CERN—Centre de Recherche Nucleaire
- CME—Coronal Mass Ejection
- DDD—Displacement Damage Dose
- GCR—Galactic Cosmic Rays
- GPS—Global Positioning System
- LET—Linear Energy Transfer
- PSYCHIC—Prediction of Solar particle Yields for Characterization of Integrated Circuits
- SEE—Single-Event Effects
- SPE—Solar Particle Event
- STEREO—Solar Terrestrial Relations Observatory
- TID—Total Ionizing Dose
- WC—Worst Case
- Z—Atomic Number

Coronal Mass Ejection Simulation



<http://iswa.gsfc.nasa.gov/iswa/iSWA.html>



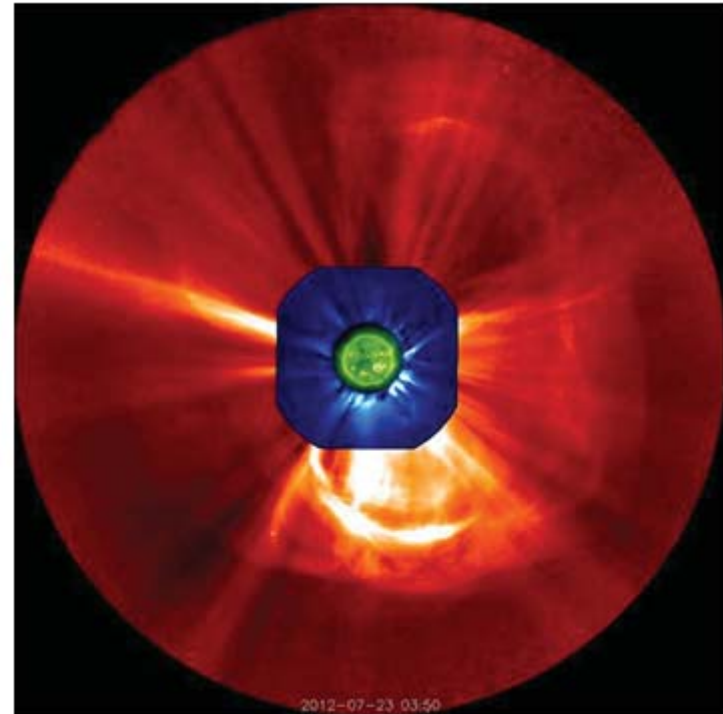
A Near Miss

Place Holder for Solar Particle Event
Video from NASA Science
Visualization Studios

Why Do We Care About Solar Weather?



- Carrington event (Sept. 1859) was largest solar particle event observed
 - Solar particle event reached Earth 4-5x faster than a normal event
 - Aurorae seen south to Havana and Hawaii, and North to Queensland
 - Colorado miners awakened by aurorae bright enough to read by
 - Telegraphs in Europe and America failed; operators got electric shocks
 - Minimal damage due to limited electrical and telecom infrastructure
- Atmospheric and Environmental Research and Lloyds of London estimate cost of Carrington-like event to current global economy of \$2.6 trillion
 - Entire Solar Cycle 24 caused \$2 billion in losses to space hardware



- Onset of Carrington-like event that missed Earth, July 23, 2012 as seen from STEREO A satellite



Outline

- I. What are the threats posed by space weather?
- II. Earth-Sun interactions and threat mechanisms across 150 million km of empty(?) space.
- III. What is NASA doing to characterize space weather?
- IV. Mitigation
- V. Slower moving threats—long-term solar variation, climate change, etc.
- VI. Conclusions

What Infrastructure Does Space Weather Threaten?



Electrical Power Grid and all it supplies at risk from geomagnetic storm.

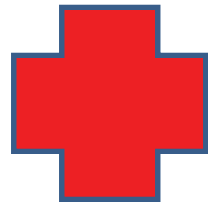
Energy, finance, water, health, transport and government infrastructure may also be compromised



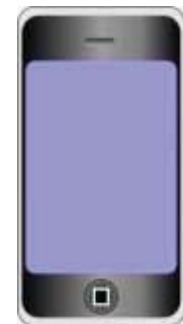
Satellites (GPS, telecom, weather, etc.) at risk due to charging, single-event effects, geomagnetic storm



Electronics threatened by geomagnetic storm and secondary neutrons



Restoring some services could take years!

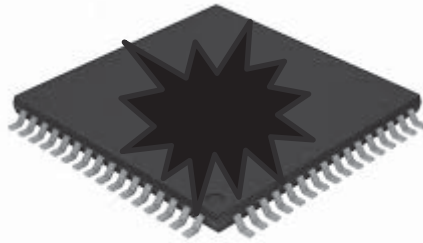


Telecommunications infrastructure damaged by geomagnetic storm.



Threats to Satellites

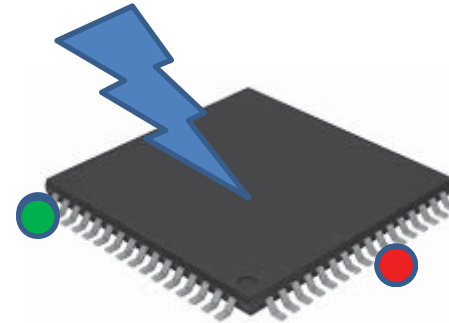
Destructive Single-Event Effects



Affect only a single die

- Energetic particle hits sensitive node in part, causing complete functional failure.

Nondestructive Single-Event Effects



- Energetic particle hits sensitive node in part, corrupting output or functionality.

Spacecraft Charging Effects

- Solar particle events inject charges into radiation belts, resulting in electrostatic discharge induced component failures .

Radiation Dose Effects

- Cumulative exposure to space radiation causes components to degrade and eventually fail.

Can affect many parts simultaneously

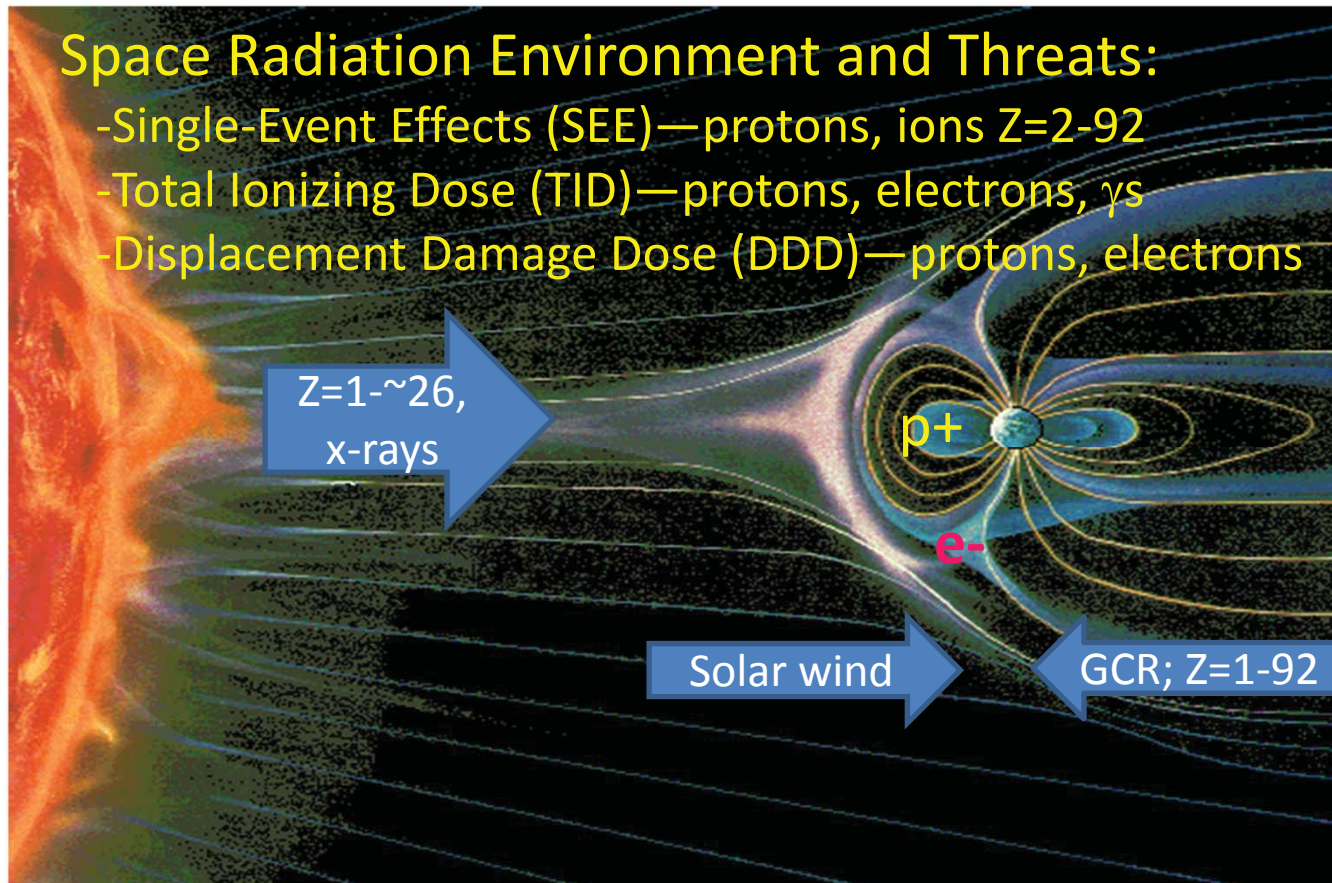
- Highest risks likely to commercial telecommunication, satellite television
- Satellites with sensitive imagers likely vulnerable
- GPS less vulnerable because normal environment is already challenging

Threats to Electrical Power Infrastructure



- Threats to electrical power
 - Space weather can cause current surges in electrical wires
 - Transformers can overheat and fail or be damaged by overvoltage/current
 - Current can flow even when power sources disconnected
- Factors affecting vulnerability
 - High magnetic latitude (North or South) increases risk
 - Long transmission lines exacerbate risks
 - High ground conductivity gives rise to higher induced currents
 - Proximity to salt water increases current levels
 - Single-phase transformers more likely to overheat
 - High voltage lines conduct higher currents
 - In US, most vulnerable area is US East Coast
- Mitigation
 - Networks of capacitors to smooth out current surges
 - Modernizing transformers and other infrastructure

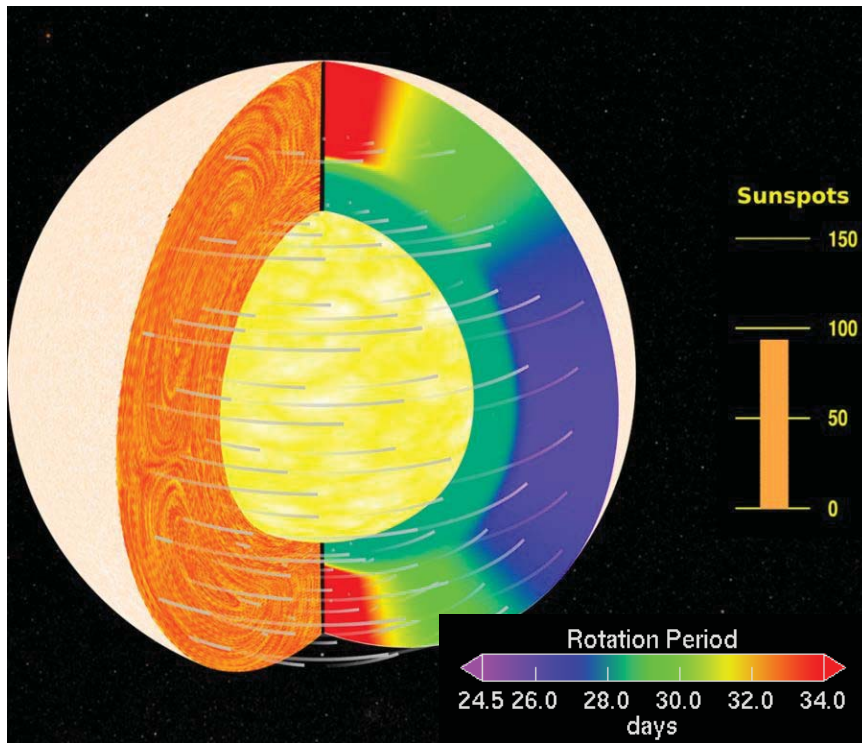
Sun-Earth Connections



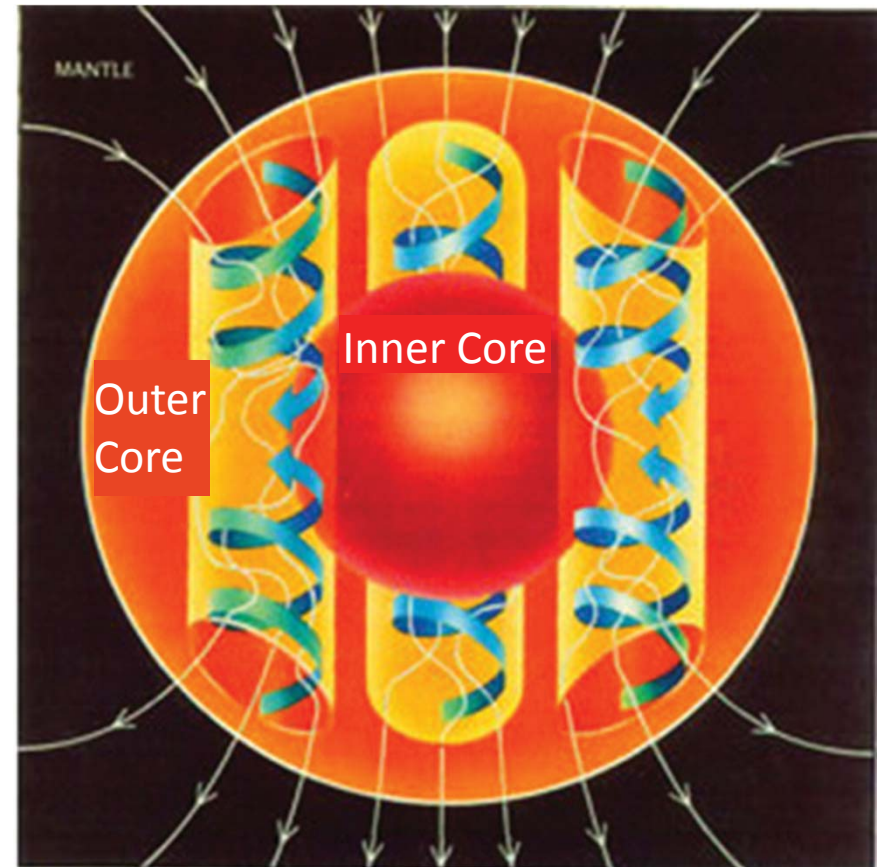
Adapted from K. Endo,
Nikkei Science, Japan

- Solar Particle Events (SPE) pose great threats to spacecraft, but solar wind also lowers GCR flux, so background threat may be lower
- Terrestrial threats from SPE induced geomagnetic storms, secondary neutrons
 - Geomagnetic storms induced by impulse given to geomagnetic field

Solar and Earth Magnetic Fields

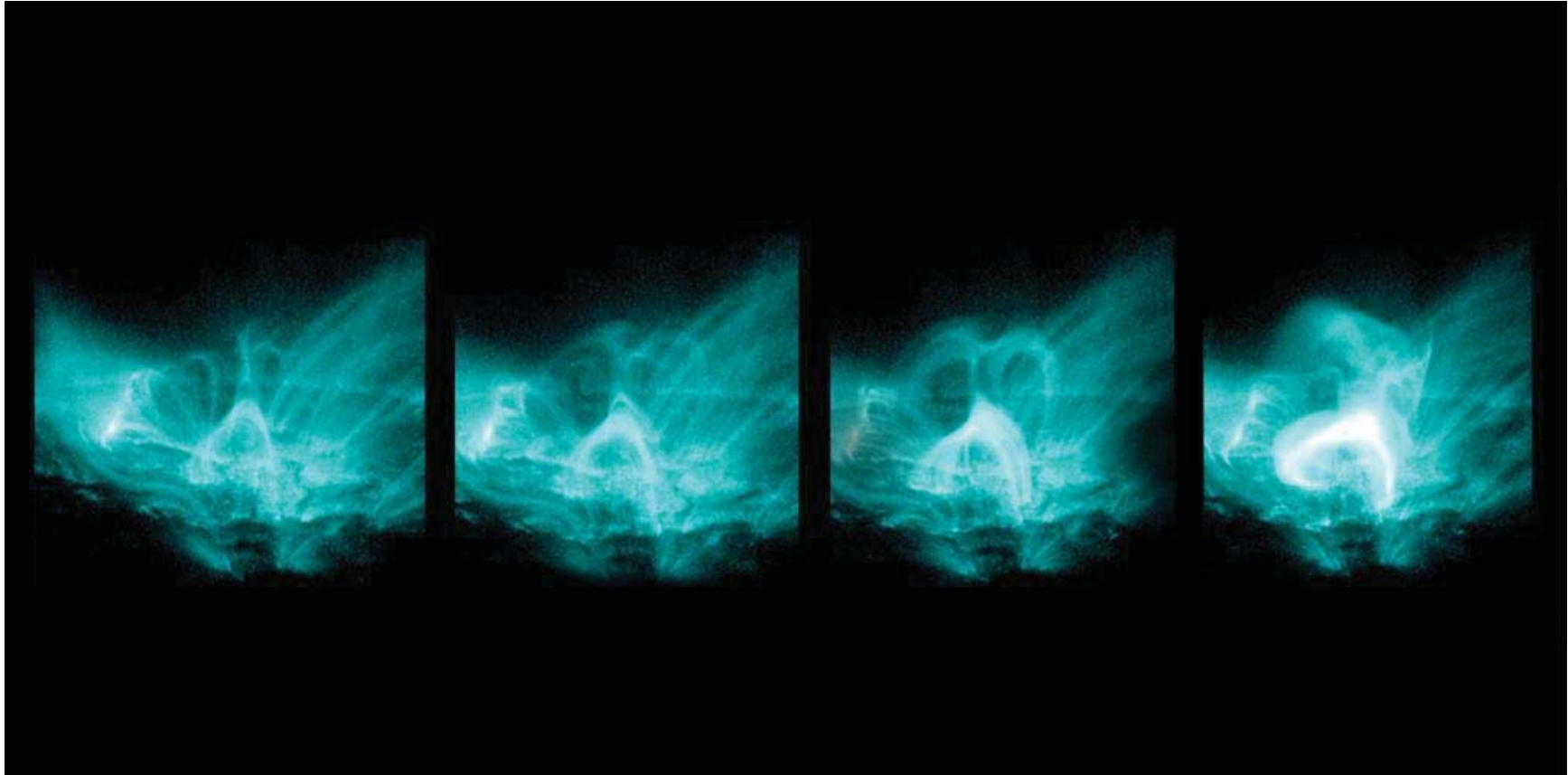


- Heliomagnetic field generated by convecting plasma near surface
 - Field flips every ~ 22 years giving rise to solar sun spot cycle



- Geomagnetic field generated by convection of liquid-iron outer core
 - Solid inner core stabilizes magnetic field, so flips occur every ~ 400000 years

Magnetic Reconnection and CMEs



Instant Replay



Place Holder for Solar Particle Event
Video from NASA Science
Visualization Studios

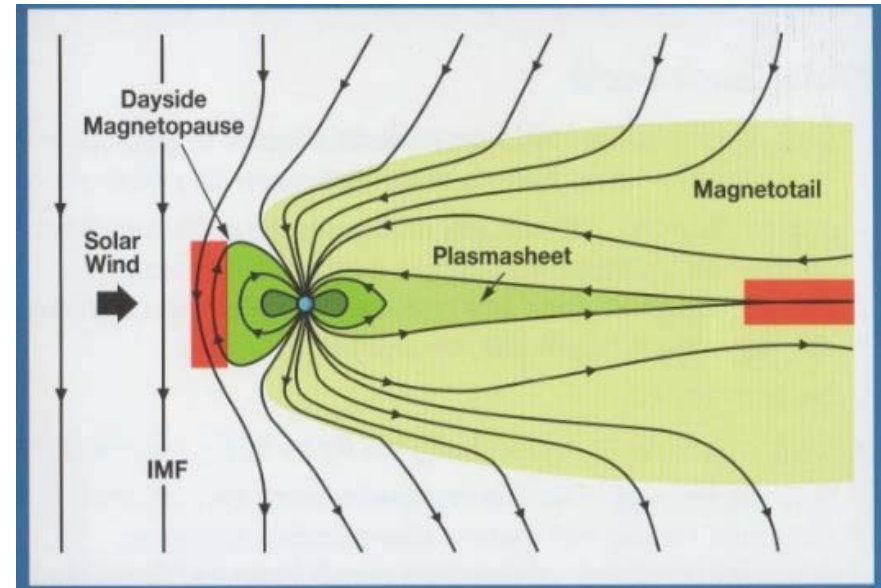


What Is Reconnection?

the disconnection and connecting again of magnetic fields

A conducting liquid, gas, or plasma must carry electric currents that separate magnetic fields from different sources, for example at boundaries between the Sun's and the Earth's magnetic fields

Reconnection changes the magnetic geometry of space.





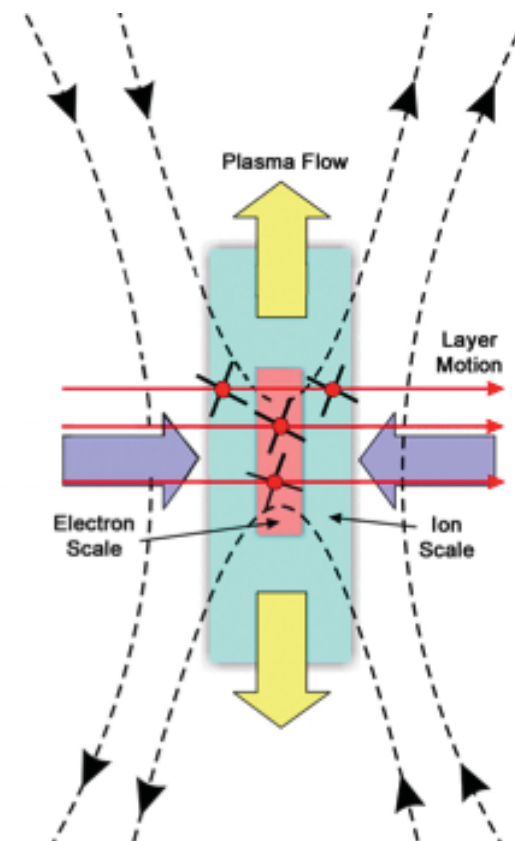
Reconnection Starts

when (per Ohm's law) a weak spot forms in a current sheet, which extends along a fissure, magnetic field lines connect through it across the current sheet.

Energy is released as two magnetic fields reconnect and change shape, pumping plasma, as in Figure, expanding the left red box in the previous figure.

We don't know how to predict when/where reconnection starts..

$$V = IR \text{ (Ohm's Law)}$$
$$E + v \times B = \frac{m_e}{e} \frac{dv_e}{dt} - \frac{\nabla \cdot \vec{P}_e}{en} + \frac{J \times B}{en} + \eta J$$





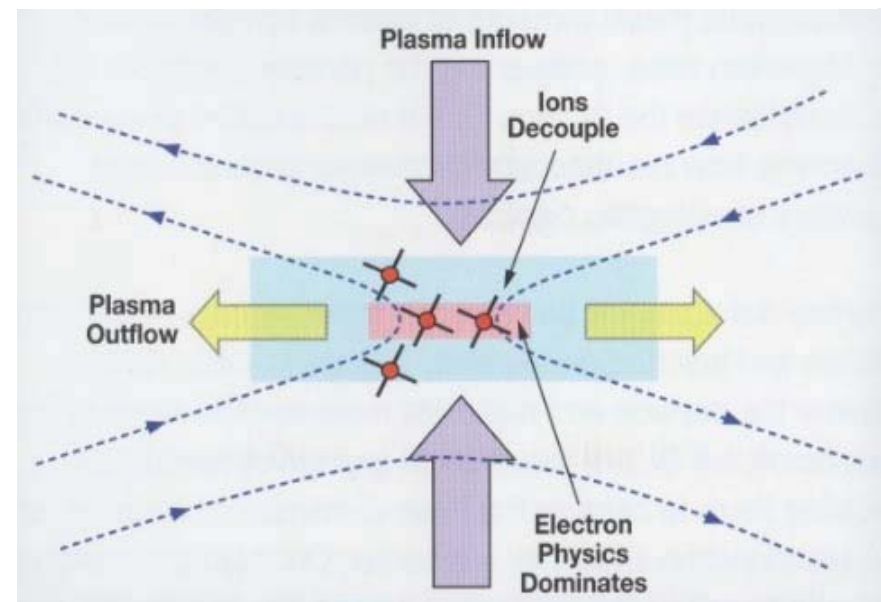
Reconnection Yields

explosive energy releases when a magnetized plasma region is stretched out by plasma flow, creating a current sheet between stretched regions within the plasma.

Tension forces (per Newton's 3rd law) accelerate plasma away from the fissure in the current sheet and into the fissure from the two inflow regions creating a plasma pump as the region disconnects into two separate regions, as in the Figure, expanding the right red box in the earlier figure.

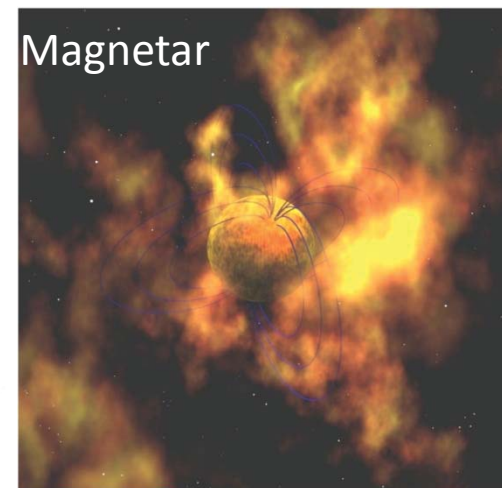
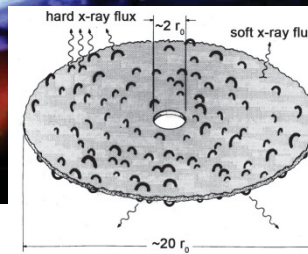
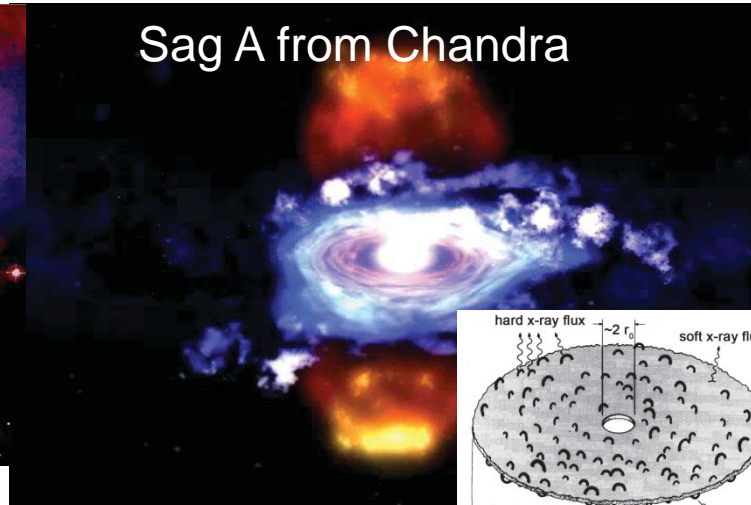
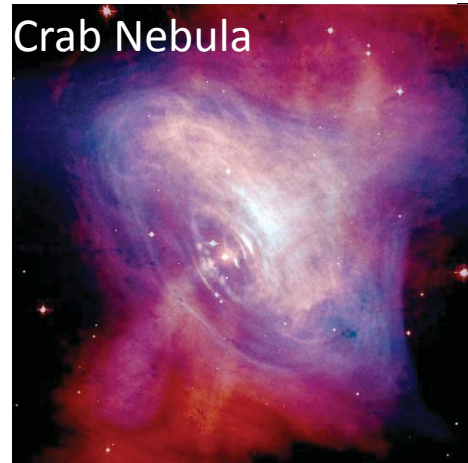
$m\mathbf{a} = \mathbf{F}$ (Newton's 3rd Law)

$$\rho \left(\frac{\partial \vec{v}}{\partial t} + (\vec{v} \cdot \nabla) \vec{v} \right) = \frac{(\vec{B} \cdot \nabla) \vec{B}}{\mu_0} - \nabla \left(p + \frac{B^2}{2\mu_0} \right)$$

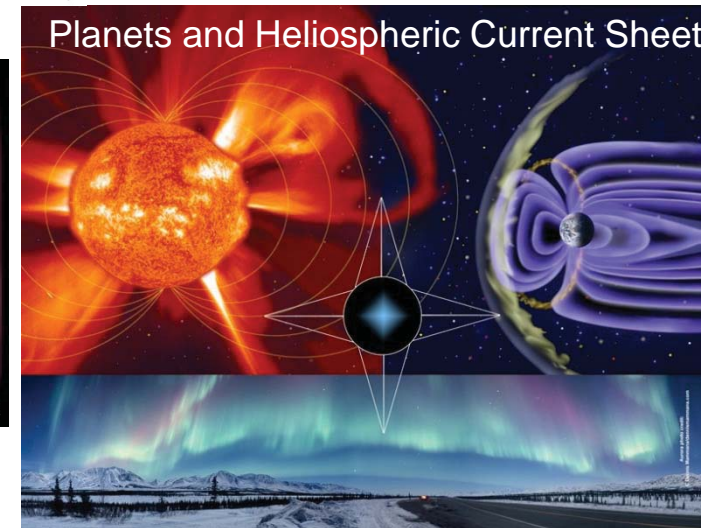
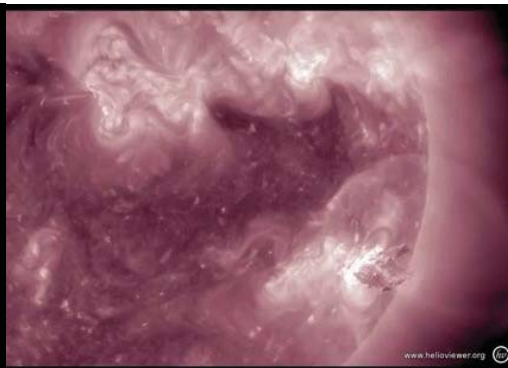
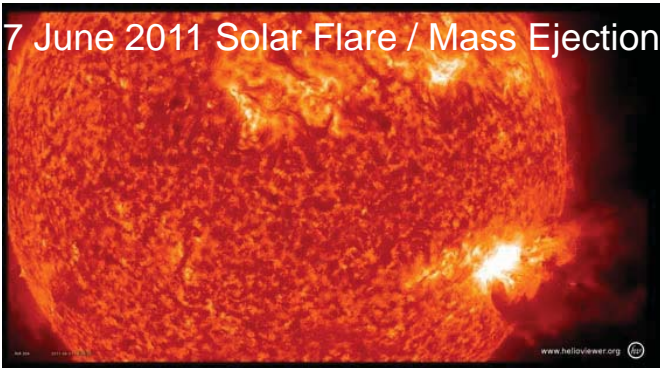


We don't know what makes reconnection explosive...

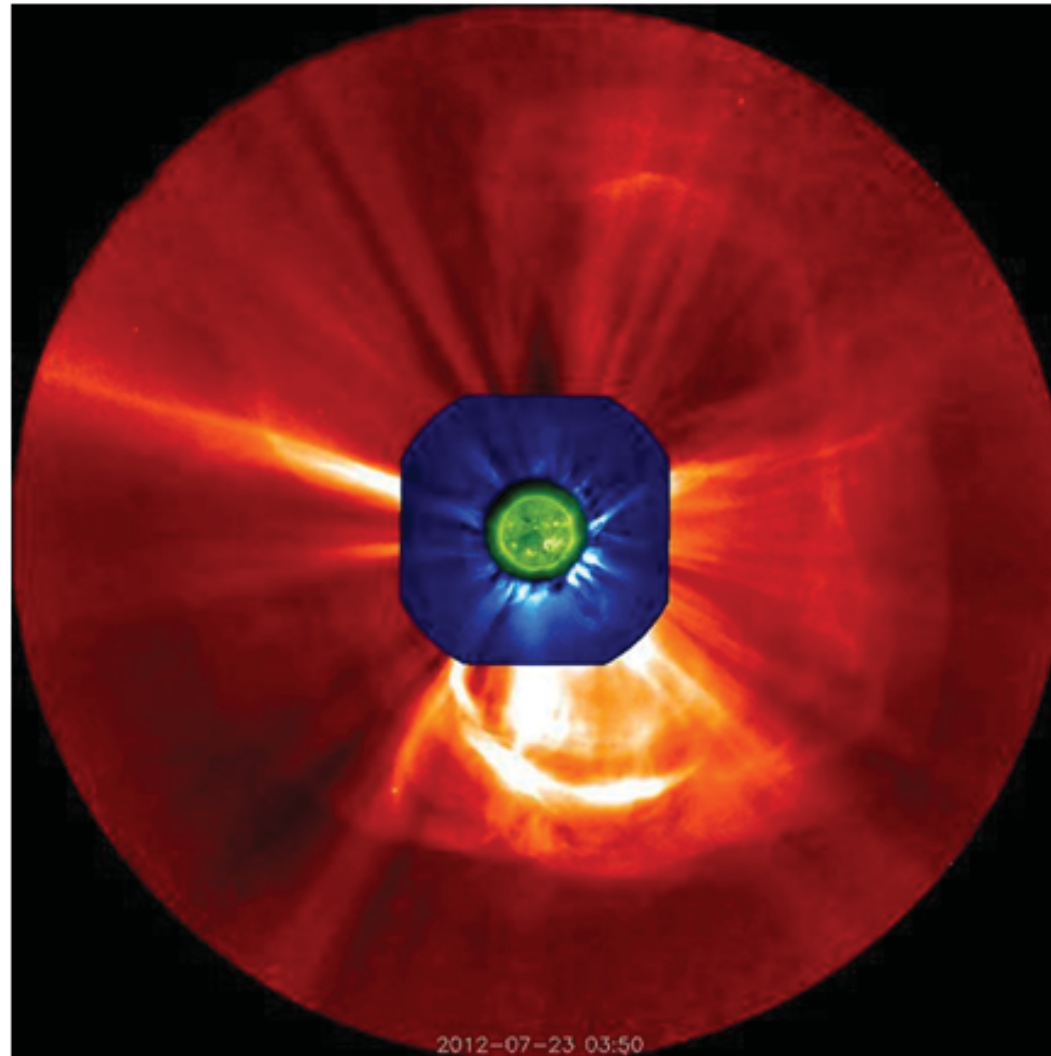
Magnetic Reconnection is Universal



7 June 2011 Solar Flare / Mass Ejection



Solar Particle Event

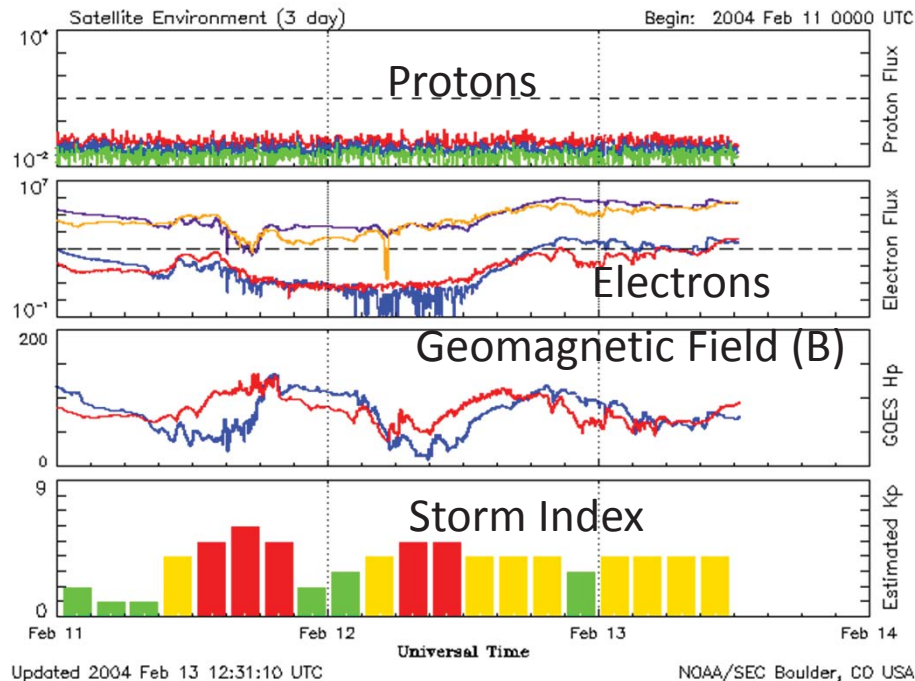


Another One!



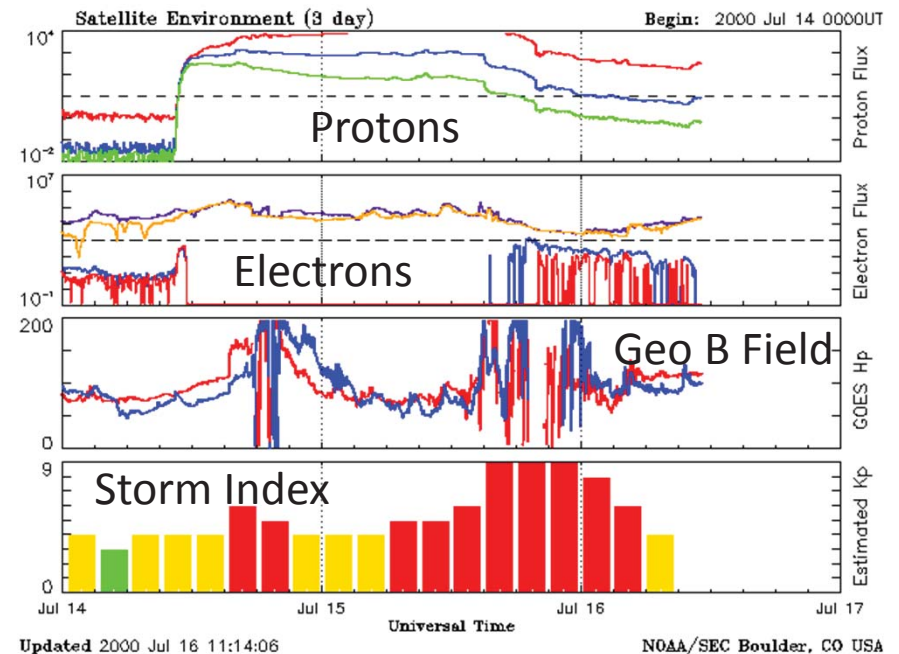
Place Holder for Solar Particle Event Video from NASA Science Visualization Studios

Effects of Solar Particle Event at Earth



Solar Quiet Conditions

- Proton and Electron Fluxes low
- Geomagnetic field fairly stable
- Solar storm Index moderate



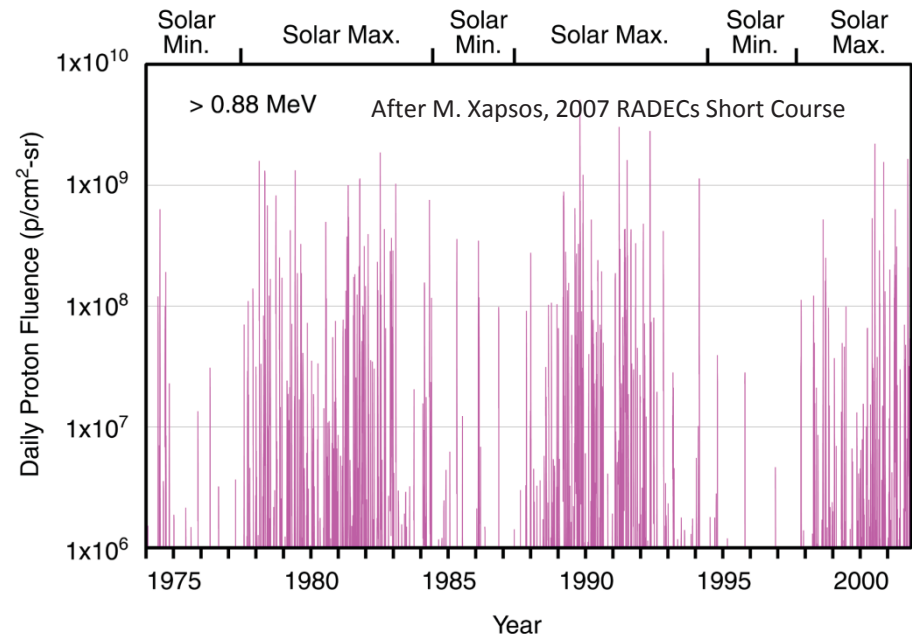
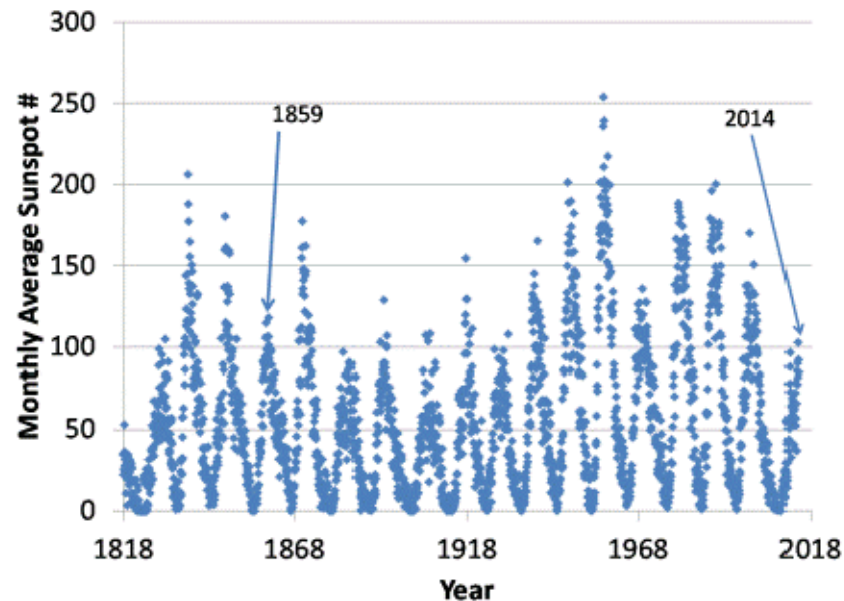
Bastille Day SPE, July 14, 2000

- Solar proton flux rises $>10^5 \times$
- Large geomagnetic oscillations
- Solar Storm Index maxed out.

NOAA Space Weather Prediction Center, <http://www.swpc.noaa.gov/>



The Solar Cycle



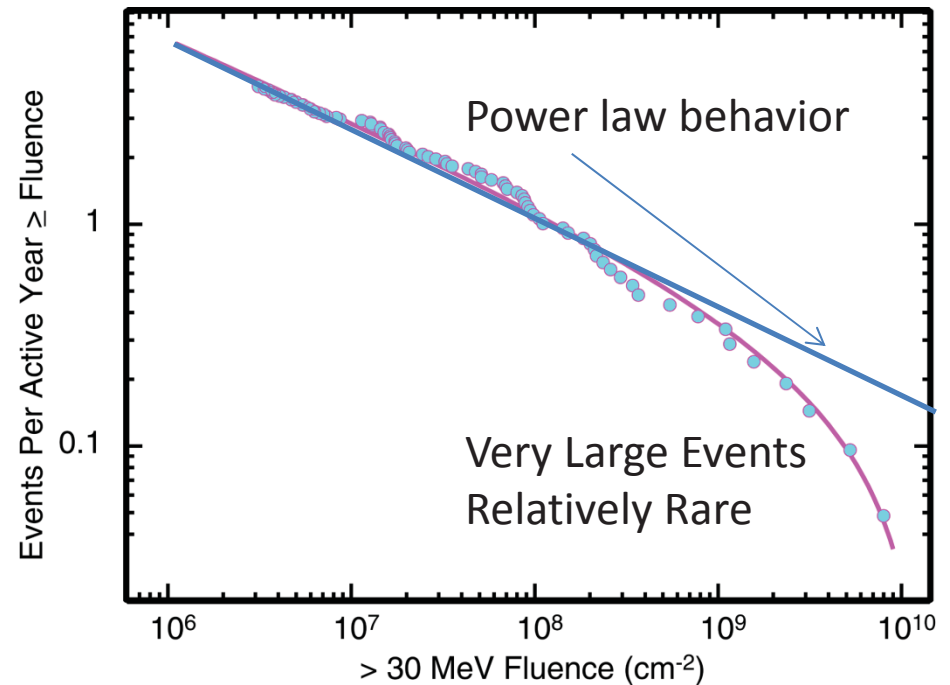
- Solar magnetic and energetic particle activity correlates with sunspot number.
- These follow a roughly 11-year cycle
 - 7 years active and 4 years inactive.
 - Large solar particle events can occur any time but most likely in solar max

- Solar Maximum has highest particle fluxes
 - 96.4% protons
 - 3.5% alpha particles
 - 0.1% heavier ions (not to be neglected!)
 - One CME yields $>10^9 >30$ MeV protons/cm²
 - Fluxes $10^5 >30$ MeV protons/cm²/second

Solar Particle Event Size Distribution

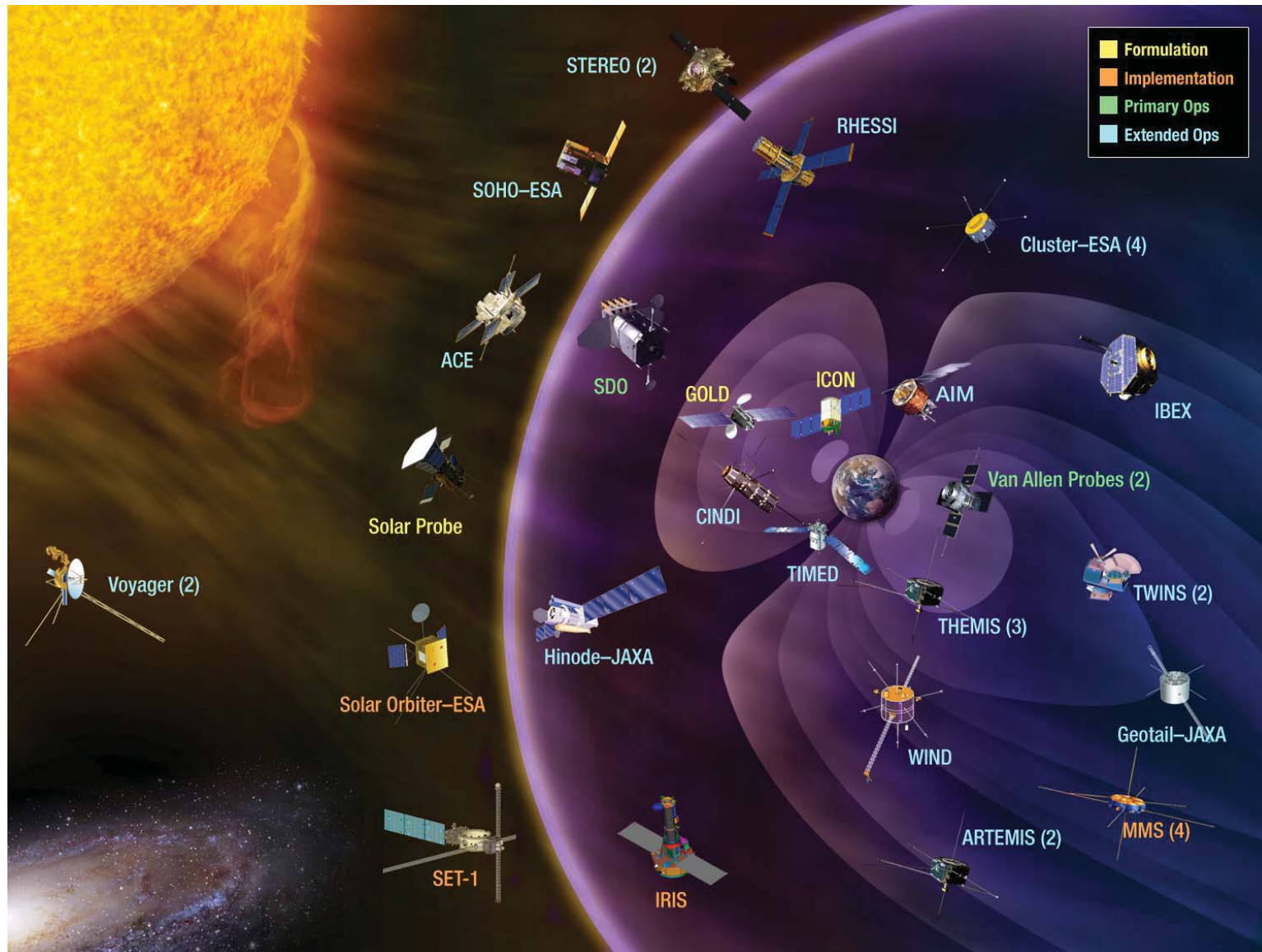


- Event Sizes span more than 4 orders of magnitude in energy and particle fluence
 - Smaller event sizes follow power law function
 - Larger event sizes fall off much more rapidly than power law
- Carrington-type event is extremely rare
 - Statistics too poor to predict frequency
 - July 2012 event doubled sample size of such events
 - Demonstrates advantage of a robust heliospheric observatory

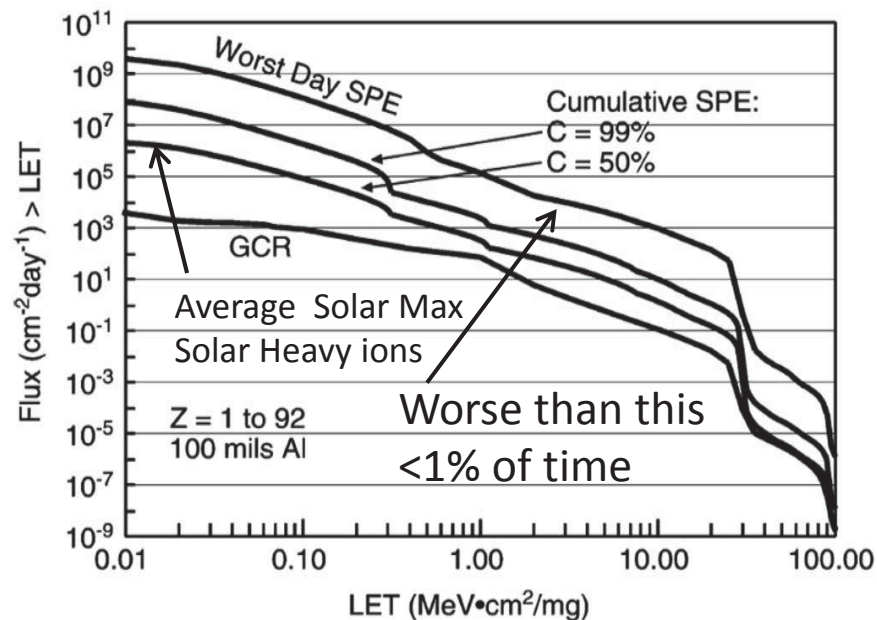


M.A. Xapsos et al., IEEE TNS, Dec. 1999

What is NASA Doing? Heliospheric Observatories

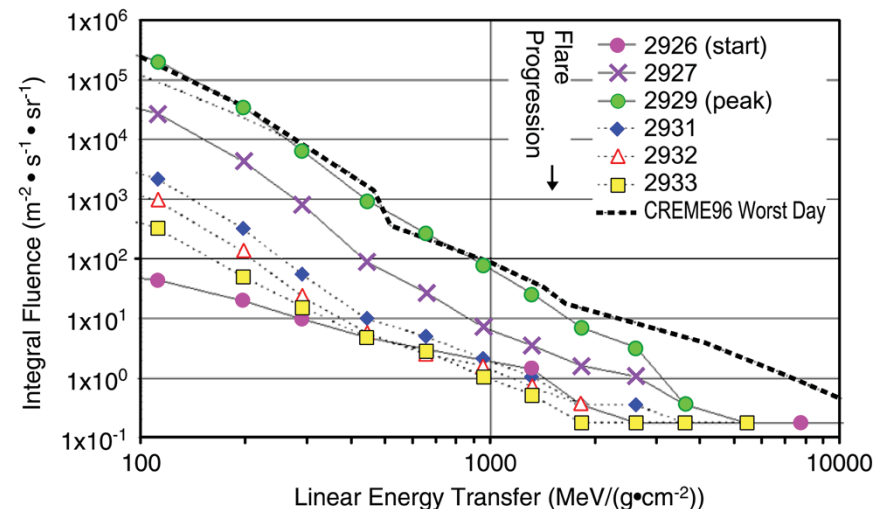


What Is NASA Doing? Modeling and Validation



After M. Xapsos, IEEE TNS 2007, p. 1985
Results include elements from atomic number $Z = 1$ to 92.

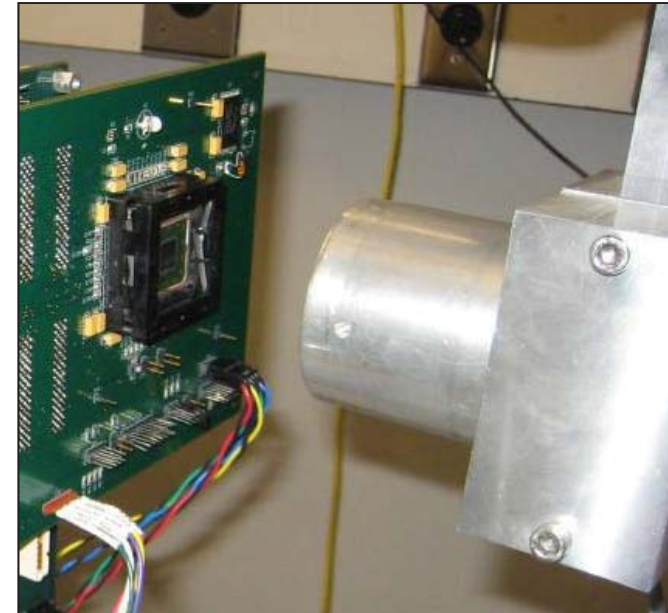
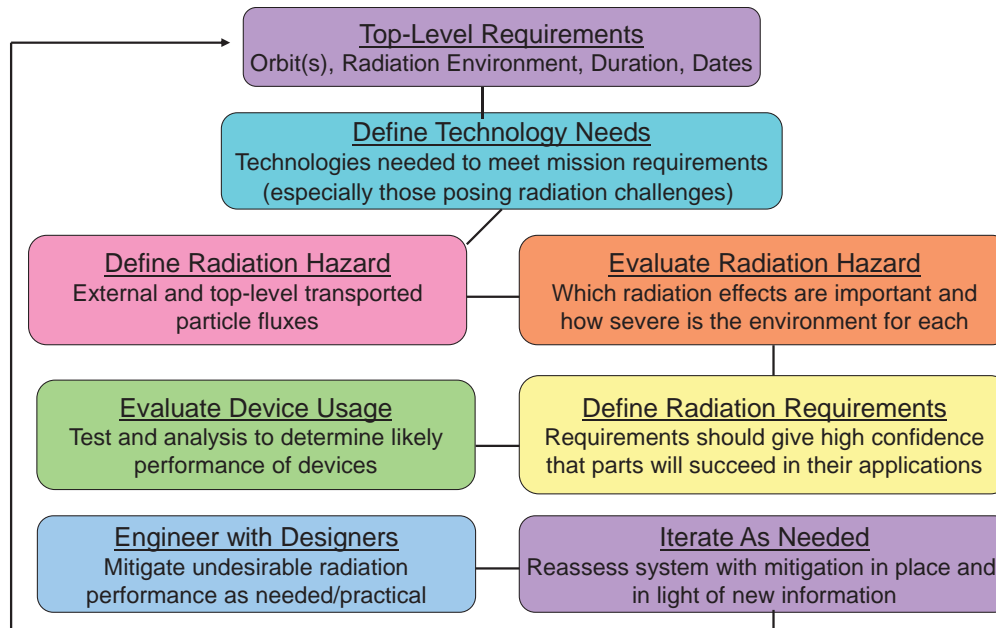
- Linear Energy Transfer (LET) measures how much charge an ion track leaves in a semiconductor device
 - Depends on ion species (heavier is worse) and energy
- PSYCHIC model by M. Xapsos estimates heavy-ion fluxes for any confidence



C.S. Dyer et al., IEEE TNS, Dec. 2002

- Study of Solar Cycle 23 showed 3 events approaching standard “worst-case” (WC) solar heavy-ion model
 - Model is not overly conservative
 - Events comparable to WC expected every solar cycle
- Carrington-like events over 2 orders of magnitude higher fluxes

What is NASA Doing? Testing and Radiation Hardening



- Satellites most vulnerable to space weather
- NASA's radiation hardening approach emphasizes collaboration with designers
 - Goal is to achieve robust operation, high performance and economical design
 - Involves part selection and system design
 - Approach iterates until requirements met
- Testing done at accelerators and other radiation sources
 - Goal is to make test as realistic as economically possible
- Models used to extrapolate and bound application performance

Solar Event Survivability—In One Messy Slide!



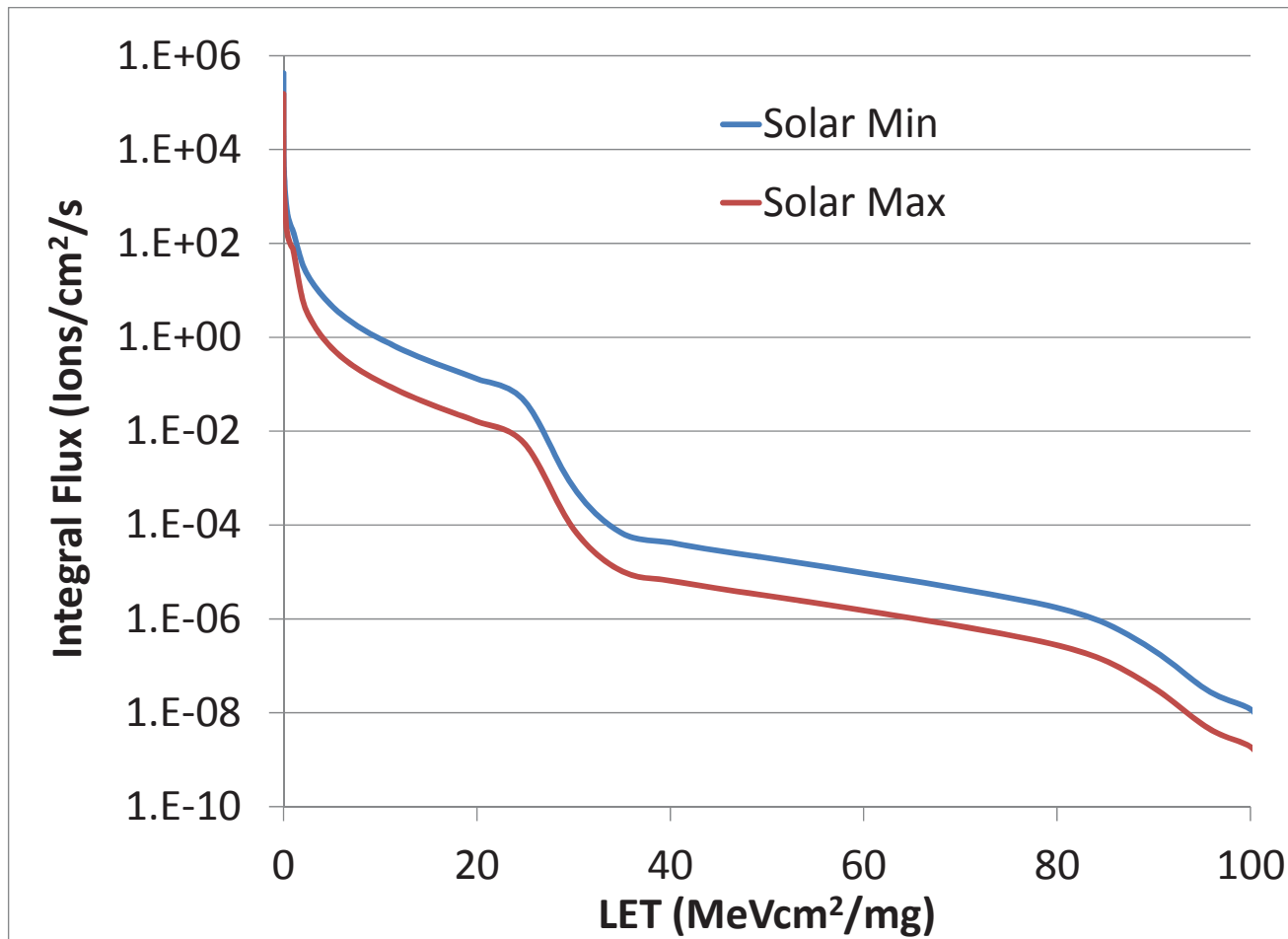
Spacecraft Charging

- Two main threats
 - Surface Charging—charges pile up on dielectrics and ungrounded metal until breakdown occurs
 - Sensitive to low-energy environment
 - Mitigation: Ensure a path to ground that avoids sensitive electronics
 - Deep Dielectric Charging—high energy charges penetrate dielectrics and accumulate until breakdown occurs
 - Insensitive to low-energy environment
 - Mitigation: shielding
- Critical Factors
 - Particle Flux and duration
 - Below critical flux, no accumulation
 - When in the mission event occurs
 - Early in mission materials are wet and more conducting

Single-Event Effects

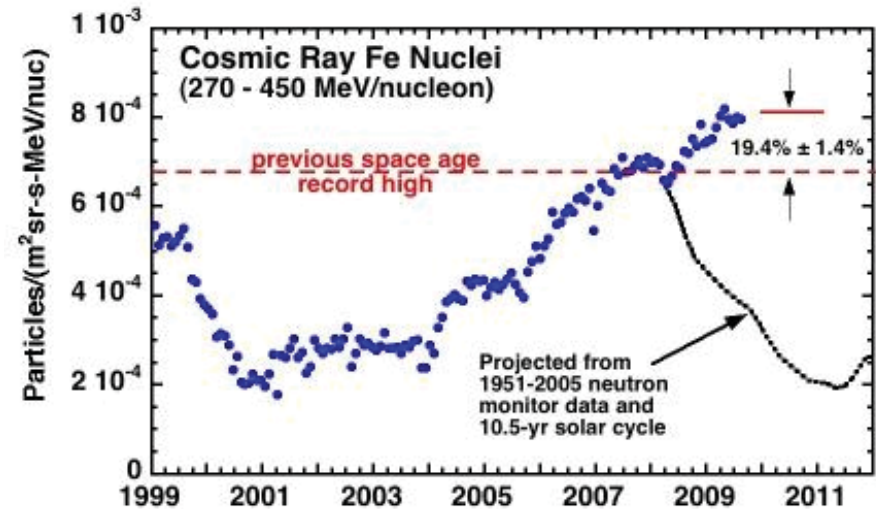
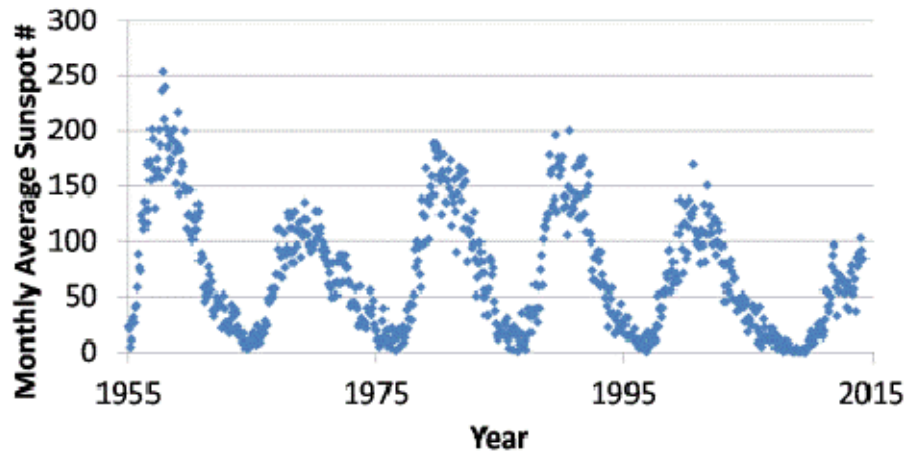
- Three levels for hardening
 - Hardening by process
 - Use radiation hardened parts
 - Circuit hardening
 - Mitigate consequences of part misbehavior
 - System-level hardening
 - When all else fails
- Nondestructive SEE
 - Redundancy (ECC, triplicate voting)
 - Also, derating performance, watchdog circuits, etc.
- Destructive SEE—best to avoid threat
 - Redundancy is ineffective
 - Select immune parts/avoid risky applications
- Rates can rise 10-100x during solar event
 - Need to ensure adequate margin

Other Threats Affected by Solar Cycle

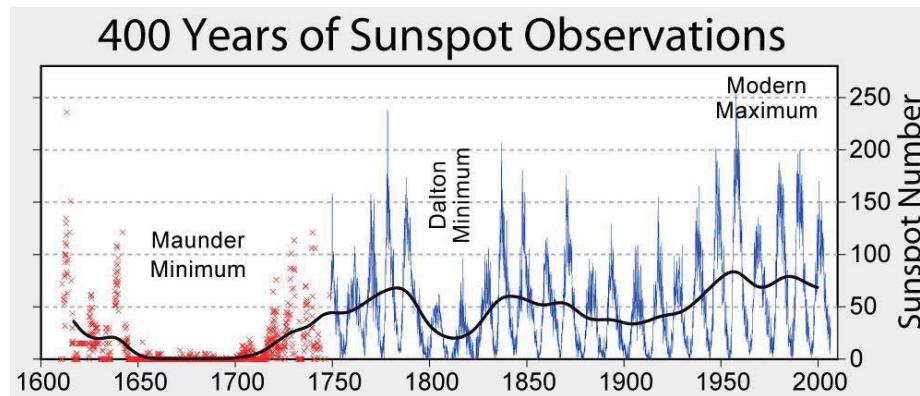


- Solar Cycle Affects Galactic Cosmic Ray Flux
 - Stronger solar wind keeps out GCR during solar Max
 - GCR flux and background SEE rates are highest during Solar Min

This Solar Cycle is Different



From http://www.nasa.gov/topics/solarsystem/features/ray_surge.html



http://www.globalwarmingart.com/wiki/File:Sunspot_Numbers.png

- Last Solar Min ~50% longer than normal
- Current Solar Max also weak
- Deep solar Min → higher GCR fluxes
 - NASA's Advanced Composition Explorer (ACE) showed up to 20% increase
- Are we starting a Grand Solar Minimum?
 - Past Minima had cold temperatures
 - Probably not: more active than Dalton or Maunder Minima



Conclusions

- Space weather poses increasing risks to critical infrastructure
 - Satellite assets , power grid, information technology, communications and through these sectors nearly every other aspect of the economy
 - Carrington-type event occurring now could cause \$2.6 trillion in damages
- Very large solar particle events are rare, but have high impact
 - Estimating frequency of occurrence is problematic due to poor statistics
 - Multiple Satellites observing the Sun from multiple angles increases the probability of seeing such events, greatly improving the statistics
- NASA addressing the issue by
 - Observing and modeling the space radiation environment
 - Testing critical components
 - Hardening critical space assets
- Understand of Sun-Earth connections is still evolving
 - Current weak solar cycle provides new interesting understanding
- What will the 6th solar cycle of the space age bring?